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The challenges and possible solutions of horizontal axis wind turbines as a clean energy solution for the future

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ABSTRACT

This paper presents a review of existing and emerging wind power technologies in light of the evident trends of the industry, and describes the challenges these technologies will face if wind turbines were to become a significant and reliable source of clean energy of the future. Apart from withstanding both the cost pressures against other forms of renewable and non-renewable technologies and the technical and design challenges for efficient and enhanced performance under all weather conditions, a major hurdle that must be overcome is to make the wind farms acceptable to the general public. Although there is now a greater awareness amongst world population about the perils of climate change, the issue of wind turbine generated noise, land use, fauna deaths and visual impacts have to be adequately addressed to ensure continued political and public support for the technology to flourish. These are the viewpoints against which emerging technologies are reviewed and the capacity of some of them to address these issues explored.

Contents

Abbreviations: AWEA, American Wind Energy Association; CCGT, combined cycle gas turbine; CO_2, carbon dioxide; CSG, coal seam gas; CSP, concentrating solar power; °C, degree Celsius (or centigrade); °E, °N, °S, °W, degree east, north, south and west; DK, Danish Kingdom; EIA, energy impact assessment; GW, giga watt; HH, Henry Hub (in relation to gas price); ICOADS, comprehensive ocean-atmosphere data set; IEA, International Energy Authority; kW, kilo watt; LCOE, levelized cost of electricity; LNG, liquefied natural gas; M (or m), meter; m/s, meter per second; MMBtu, million metric british thermal unit; MW, mega watt; MWh, mega watt hour; NBP, national balancing point; NCDC, National Climatic Data Centre; NESDIS, National Environmental Satellite, Data, and Information Service; NOAA, National Oceanic and Atmospheric Administration; PTC, production tax credit; PV, photo voltaic; TFC, total final consumption; UK, United Kingdom; UNEP, United Nations Environmental Program; US, United States

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1. Introduction

With climate change and environmental concerns growing, the need for a greener world with cleaner energy has never been greater. Yet predicting a timeline when, how and with what technologies it will be achieved is shrouded with conflicting claims and controversies. The Rene21 Global Future Report of 2013 [1] paints an overly optimistic picture, while "Tracking Future Energy Progress" report [2] in the same year of 2013 by the International Energy Agency (IEA) appears to suggest that progress towards clean energy had stalled based on the assessment that the cleanness of an average unit of power in the world has remained virtually unchanged over the last 20 years. Greenpeace [3] or Bloomberg New Energy Finance [4] are upbeat about rapid transformation of the economy towards renewables and smart grids while fossil fuel industry and conservative research groups are in complete denial of the very climate change itself and advocate either status-quo or further growth of fossil fuels [5].

It is against this background of the clashes of future visions that we have undertaken this review not to resolve the clash of entrenched visions for future world, but to look objectively to identify some of the challenges that face one of the candidates of renewable power generation, namely wind power, with which the authors have been involved [6–14] and facilitating the development of various test facilities [15–21] and flow diagnostic techniques [22–29] along with conducting flow field investigations [30–44] towards applications of flow control methodologies [45–49] that may provide possible solutions and performance enhancement opportunities. Of these, particular mention may be made of the design of test facilities such as a test rig for investigating rotor dynamic stall [20], design of an anechoic chamber for measurements of wind turbine noise [17], design of a portable rain chamber that can be adapted to existing wind tunnel test facilities [15] to investigate performance under rain; development of flow diagnostic techniques such as Laser Doppler velocimeter [25–28] and multi-hole pressure [22–27,29,30] for complex three-dimensional velocity measurements; the development and validation of the highly loaded theory for wind turbine rotor design [11]; a novel high efficient wind turbine [12] for urban dwellings and innovative applications of aerodynamic principles of flow control for enhanced wind turbine performance and safer performance using exponentially decaying air vortex generators [21,48] requiring minimum energy input, Coanda jet [38] or synthetic jet actuation [45,47] to address the problems of flow separation and control of dynamic stall.

The last two decades have seen phenomenal growth of the wind turbine industry that is evident in the global wind power capacity growth in the 1996–2011 periods as depicted in Fig. 1.

Conventional power generation from coal fired is heavily subsidized by governments around the world to the tune of nearly 8% of total government revenue [51] whereas electricity production from wind power does not. Thus in terms of levelized cost of electricity (LCOE), Wind Power has been at a significant disadvantage. Yet recent data suggests that the cost of electricity from wind power in Australia and many\countries in the world have been falling fast and will continue falling as capacity\increases and technology improves making the Wind Power sector either on par or near parity with conventional power generation sectors [50]. As an example, Bloomberg [52] has shown that under Australia's carbon pricing policy, from newly built facilities, the cost of electricity from a new onshore in Australia is $A80/MWh compared to $A143/MWh for a new coal-fired power station and $A116 for a new gas fired power station. Noting further that wind energy requires no water in its operation, except during maintenance cleaning that does not happen very frequently, whereas other fossil fuel extractions and their usage do require water, a commodity that is essential to sustain life but is fast becoming scarce (Fig. 2). Additionally, wind power doesn't produce pollutants such as nitrous oxide or sulphur dioxide or particulates as coal, and to a lesser extent gas do (see also Fig. 23), and it is forecast by the IEA to make the greatest contribution of all clean energy technologies in coming decades in terms of $C0_2$ reduction (Fig. 3) [50] making wind power an invaluable asset in the quest for a sustainable environment.

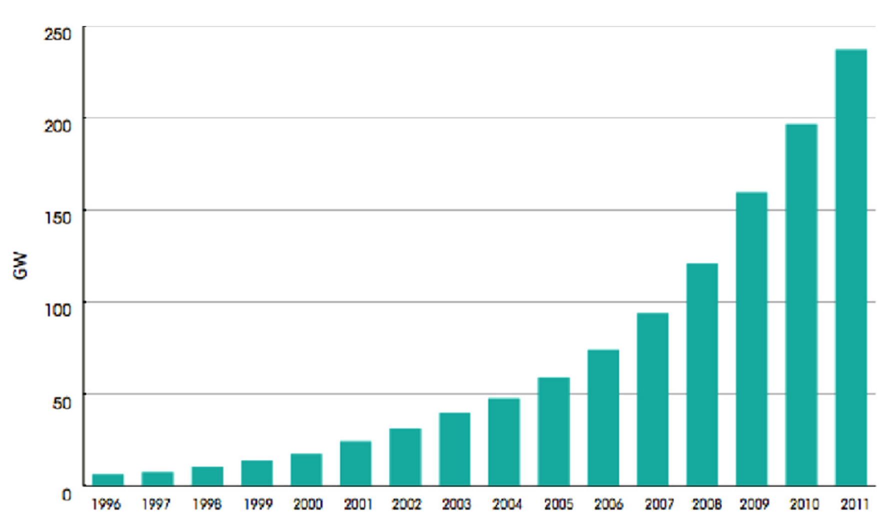

Fig. 1. Annual growth in global wind power capacity up till 2011 (taken from [4]).

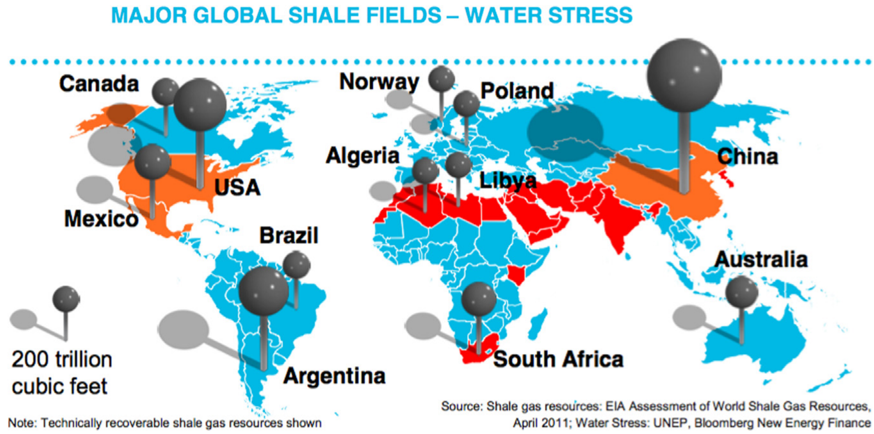

Fig. 2. Shale oil and gas extraction uses large quantities of fresh water, when drinking water is scarce (taken from [52]).

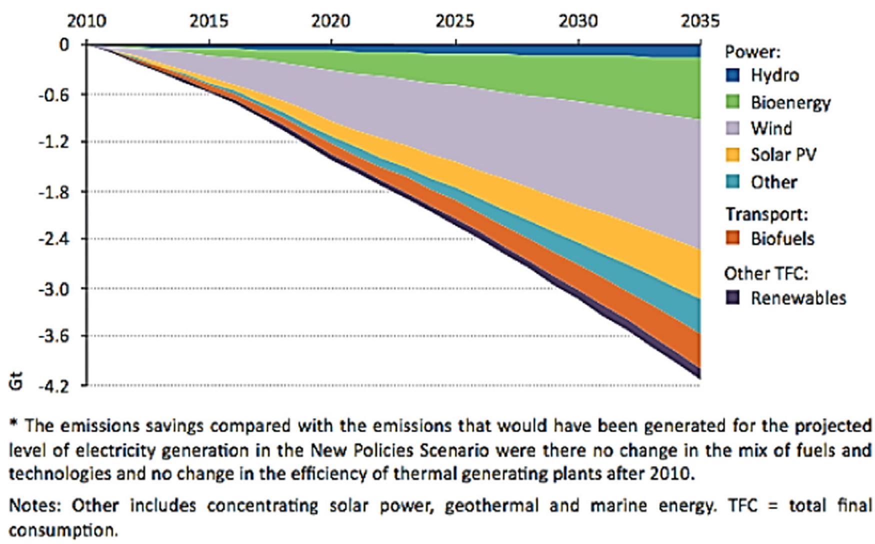

Fig. 3. CO_2 emissions savings from greater use of renewables, relative to 2010 fuel mix* in the New Policies Scenario (taken from [50]).

Despite the positive attributes of wind power mentioned above, the key challenges for the wind industry that can broadly be identified include the intermittence of wind turbine electricity supply, decline in performance over their life time, the need to expand into industrializing nations, competition with fossil fuels for investment, social acceptability challenges, various onshore and offshore challenges, competition with other renewable energy providers and government public policy consistency worldwide. In addition some unexpected and not so unexpected, but nevertheless significant new events such as the emergence of cheap coal seam gas (CSG) appearing on the US market in 2013, the concept of smart grid and the deregulation of the power market of recent years may greatly impact the future short and long term viability of a clean energy economy, and on wind power's prospects of being an important part of this. These key challenges and possibilities for Wind Power, and also for future global energy supply, will now be analysed and weighed, and some conclusions drawn.

2. The challenge of maintaining performance efficiency

Wind turbine performance generally declines over time, and in some cases, quite rapidly. In a 2012 study regarding of three wind farms—1 in the UK and two in Denmark—the results were quite stark. The UK onshore farm, using mature technology, lost half of its starting capacity factor over 15 years, and the Danish offshore farm lost closer to three quarters of its starting capacity factor in just 10 years. The Danish onshore farm fared better, losing just over 20% within 18 years - a bit closer to expectations (Fig. 4) [53].

The wind industry is well aware of this issue [54]. One response mentioned has been for companies to develop upgrades to existing turbines that can extend turbine life up to 30 years, for example the Gamesa upgrade for the Vestas V47 [53]. (And as an aside, another interesting development in the industry is competitors selling upgrade kits for each other's models!) More broadly however, there are also indications that operation and maintenance costs have been falling significantly, from around \$20/MWh for those installed in the late 90s to around \$5–10/MWh for units installed around 2005 [55].

A response to the longevity problem of offshore systems has been to design models specifically for ocean environments rather than adapt onshore models, for example the Gamesa 5 MW offshore prototype being commissioned this year [54]. These units have installation and maintenance convenience at sea and resistance to corrosion and salt accretion, plus the freedom to be larger in scale.

One issue significantly reducing performance of offshore systems is salt accumulation on the blades affecting the aerodynamics, and onshore the equivalent problem is dead bugs and general grime accreting on the surface [56] (Fig. 5). Blade cleaning it is often done after 10–12 years, as part of a major overhaul, but not always.

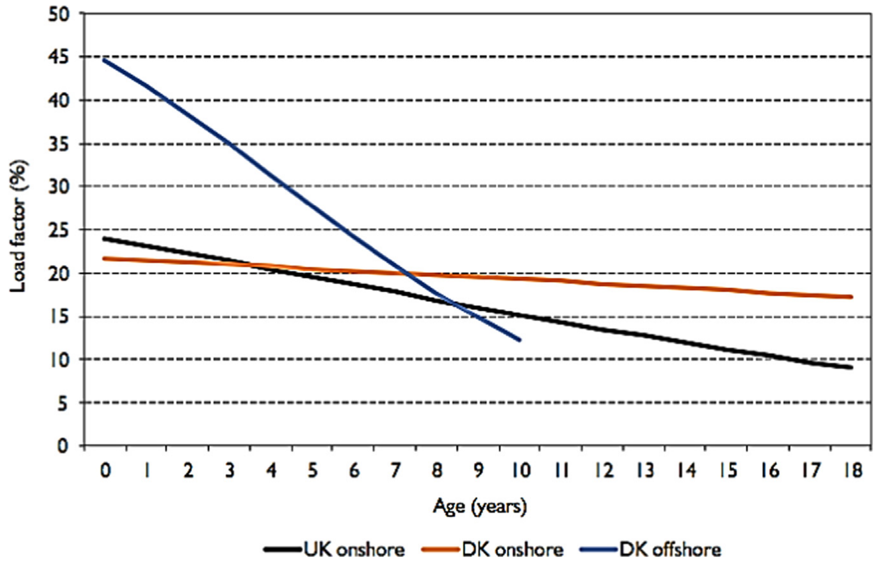

Fig. 4. Performance degradation of wind turbines over time (taken from [53]).

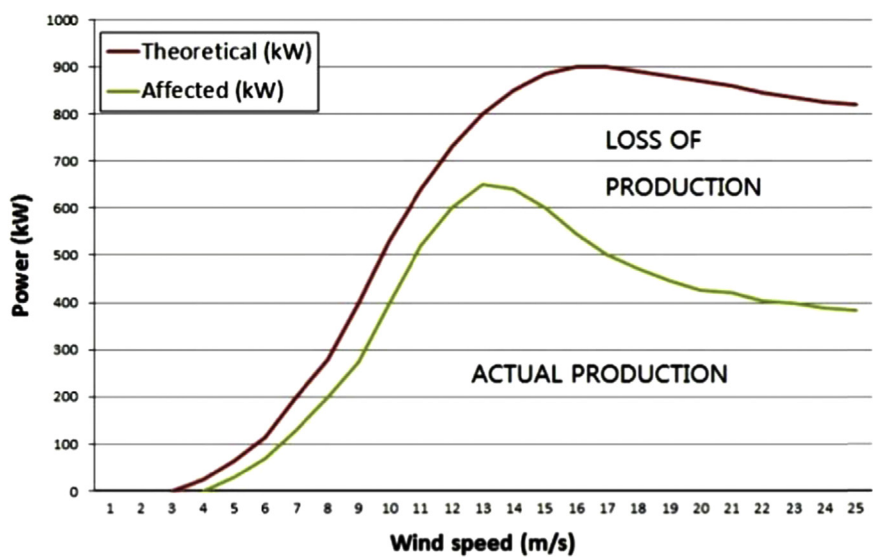

Fig. 5. Typical performance loss due to accretions on wind turbine rotors (taken from [56]).

The UK/Danish data mentioned above doesn't reveal a lift in capacity factor midway through the data collection, as may be expected if effective cleaning and other performance tweaking were done at that point, leaving open the possibility that salt and grime accretion could partially explain the unacceptable fall [56] (Fig. 6). Such results may also help explain the move in the industry towards signing maintenance contracts over 20 years, to ensure proper maintenance is done, so as to improve profitability.

Quite intense cleaning is required to remove the accretion [56] Some approaches tried have included cleaning systems embedded in the pole [56] and cleaning robots, such that an overhaul is not required [56].

Another source of performance degradation over time is the gearbox and main bearings, which generally need replacement after 10–12 years. Another response of the industry has been to develop direct drive systems that don't need a gearbox [57] with generators utilising permanent magnets. These systems are more robust in extreme winds also [57].

Fig. 6. Accretion of grime on wind turbine blade (taken from [56]).

3. The challenge of intermittent nature of wind supply

The variable or the intermittent nature of wind supply is probably the biggest hurdle wind power has to overcome. Since power grids require a reliable energy supply, energy companies are often forced to apply a cost of the extra gas turbine plant required to make up the missing guaranteed supply to intermittent of suppliers [50] in order to ensure integration of variable renewables sources like wind into a grid.

Following IEA, some idea of the integration cost can be ascertained. The integration cost is found to consist of "adequacy cost" that range from $3 to $5 per MWh of variable power generation; the "balancing cost" or the cost of the gas fuel required to make up the difference in electricity generation between the renewable energy supplied and the demand on a second by second basis, and this cost lies in the range $1–7/MWh and upgrade costs for new transmission lines and grid that can add $2–13/MWh making the total cost of integration of renewables such as wind to range from $6–25/MWh [50]. Using the worst case of $25/MWh for integrating a variable supply into the grid, wind power would still be significantly cheaper if competing with new coal or gas installations in Australia and may even be cheaper in in other countries that have carbon pricing [2]. Prices for wind power as low as $40–50/MWh have been quoted for the best wind sites [2]. However, looking at the situation in more detail, there are situations in which grid integration costs can make a very important difference to the real price of electricity to the consumer, and if not managed, this effect may increase with increasing grid integration, especially with offshore wind farms. To tackle this information, a brief explanation is first required regarding the different ways that wind power can integrate with the grid.

Much wind power capacity, especially from the smaller onshore systems, is added directly to the low voltage (240 V) grid as a feed in tariff, and as such it is indistinguishable from the consumer demand. It is thought of by grid operators as a source of varying "negative demand" superimposed on the already variable "positive demand" [58].

As an aside, this is why wind power can sometimes be accused of adding demand instability to the grid. Superimposing two irregular waveforms can increase overall variability unless advanced forecasting and control technology is used.

Because offshore systems, especially large ones, have a much more constant and reliable energy supply, they are increasingly participating in the high voltage "energy obligations" market. In this market, power is requested and sold to the grid according to a particular deal for each projected, say, half hour time segment so as to meet a particular forecast demand. If the demand isn't as high as was expected on a second by second basis, the power supplier will be "constrained" such that it only supplies the actual demand, but the difference is sorted out afterwards. With fossil fuel suppliers, they actually pay the grid for this balance that they didn't actually supply, since it wasn't needed after all (but they do take a profit margin). With wind power the opposite happens since rather than saving fuel, in many countries will they lose subsidies from the government for wind power not delivered, which, therefore, had to be wasted. So the wind power provider is paid a (hopefully, publicly transparent) "constraint fee", often of several hundred dollars per MWh of promised demand that was offered but not used, thereby having to be wasted [58].

According to the UK experience, around half of the constraint agreements with utilities are not publicly available or included in analyses however, based on information tabled in the UK parliament recently [58]. Also the constraint payments to wind energy providers are often much larger than the subsidies lost, allowing the provider to make a handsome profit when constrained. In a representative offshore project, (a UK project, but converting to Australian dollars at 1:1.64 to compare with figures quoted above), the constraint payments to the wind supplier were $361/MWh, the subsidies lost were $90/MWh and the equivalent positive payment that would have been made by a fossil fuel provider in that situation was $56/MWh. Therefore, the difference due to wind, ultimately paid by consumers, amounted to ($361–$90+$56)/MWh, or $327/MWh.

Constraints don't happen all the time of course, but they can happen a fair number of times throughout a day, and will happen more often when the grid is nearing its rated capacity, such that it has to be more vigilant in constraining supply. These payments will also potentially happen more as larger offshore wind projects are constructed which are able to supply a more constant and predictable power supply, and so be able to connect to the high voltage system. One can see from this that wind resource grid integration, along with some issues to do with lack of transparency and equity in the arrangements, has the potential to push up electricity prices to consumers in coming years as renewable energy's share increases, unless something changes.

But having said all of this, it is also widely believed that the situation will improve in the light of technological changes coming to the grid. According to Black and Veatch's seventh annual US electric utility industry report, only 3.4% of grid operators surveyed thought that meeting renewable portfolio standards was not achievable technically. New grid power standards in the US are also driving wind farms to use some traditional battery storage to improve the stability of their power supply to the grid [53]. Using battery storage from electric cars to stabilize the grid is also taking off in some countries such as Denmark, which has installed over 1400 electric car charge points, with a goal of 200,000 electric cars by 2020 (recently downgraded from 400,000 however) [59].

Some exciting possibilities (to be discussed more later) include greater grid integration between countries, offering possibilities such as one country utilizing excess wind power generation to pump water uphill into a dam in another country, and reclaim this power again on demand when it passes through a hydro generator [59]. Another possibility is storing excess power as hot water in large insulated tanks so as to offset the burning of fossil fuel in combined heat and power (CHP) systems [59]. Another possibility is smart meters that can allow two way flows of power [2] and tracking and delivery of power generated greater distances away, and which can also offer demand side load management of non-essential but power hungry household loads such as air conditioners and fridges [59], subtly changing their cycling or thermostat set points during peak times

There are a number of ways in which the wind industry itself is responding to the challenge of intermittence. The first has already been implied—the move to offshore sites where winds are often consistent enough to be relied upon in the high voltage market. The second is a technology developed by GE which involves turbine models that use a relatively small amount of energy storage in a building at the base of the wind turbine, but which use it in a clever way, in association with detailed metering and forecasting and grid integration, so as to offer the grid a reliable supply for 15–60 min ahead [54]. There is a growing importance in wind farms being able to promise and deliver a given amount of power over a short but defined period, which this technology enables.

Another concept (at an earlier stage of development) involves compressed air storage and the use of a small turbine and electric generator to constantly supply this pneumatically generated power to the grid [2]. New prediction software applications and methods also give fossil-based backup generators more time to ramp up if required. Michael Revak, vice president of Siemens, has also mentioned that new management systems, analytical methods and algorithms are being developed to improve the data management and utilization of their wind energy systems [60], showing a trend towards developing advanced ways of managing electrical variability.

The fierce competition for the projects that have still gone ahead in 2012 has led to a profitability situation that is very tight in wind

power's traditional homes of Northern Europe and North America, plus there have been ongoing policy setbacks and uncertainties especially in the US. Therefore it has become very important for the industry to establish itself in new markets that are more positive [54]. The opportunity that presents itself is the developing world but the challenge will be to supply generation capacity and consistency to meet the phenomenal the growth in electricity demand of these nations, and also to attract the required investment.

4. The challenge of global industrialization

A challenge for the wind industry, which is also a unique opportunity, is to service with energy the increase in population and industrial development of markets of the non-OECD countries such as China, South Africa, India and Brazil, among others. The speed of development, together with the renewable intermittence issue mentioned, has been expected—especially in the more conservative outlooks, to lead to a default position in these industrializing nations of relying mainly on fossil fuels [61]—buying old-style coal-fired power technology (Fig. 7), [1] plus some easy-to-install gas-fired/combined cycle generators and nuclear plants, rather than committing their grid supplies to a high share of renewable energy supply such as wind and solar.

This would not imply that these countries are negatively disposed towards renewables. The developing world bloc of countries is trending towards becoming the mainstay of the renewable energy sector in coming decades (Fig. 8). They are generally enthusiastic about using them. But the sheer urgency to supply power, along with cheap fossil fuel prices, are putting immense pressure on them to invest heavily in coal and gas generation, as can be seen in (Fig. 7) plus also nuclear, in some cases. And the coal-fired equipment they are projected to buy is mostly of the cheapest, dirtiest kind, namely subcritical.

Denmark has a plan to be 100% energy self-sufficient using renewables within 40 years [59] a policy that is leading them to simply find a way to make a renewable energy-based-grid work, no matter what. To be fair, it is probably easier for a developed country like Denmark to do something like that than say for India to pull it off, since there are so many people in poverty, whose priorities are

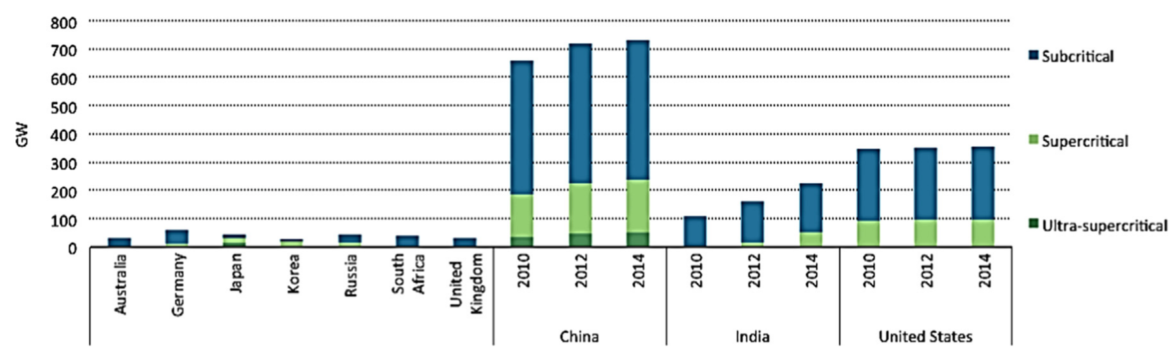

Fig. 7. Types of coal-fired generation being adopted by different countries (taken from [1]).

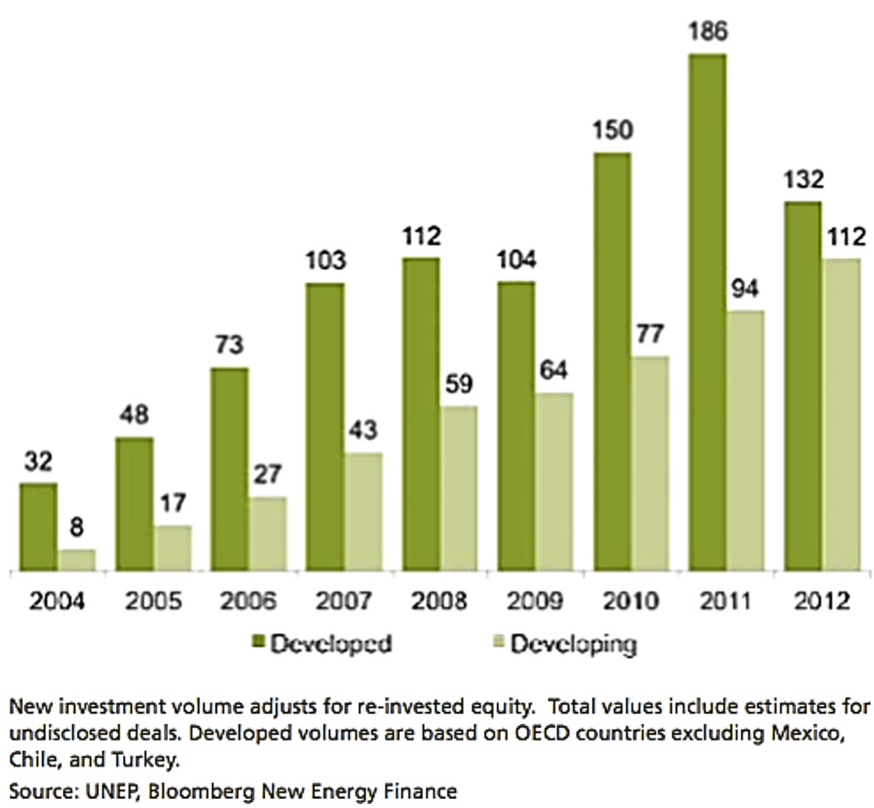

Fig. 8. Billions of dollars invested in renewable energy in developed vs developing countries (taken from [4]).

fundamental. The wind industry would also need to find the means of meeting the demand—having the manufacturing capacity to supply that much power in a timely fashion. The great danger is that the mix of renewables in these developing countries, despite growing many folds, will end up being comparatively small overall, and by default lock these nations into a fossil-fuel future over coming decades, and the pollution and climate effects that brings. The interplay of these factors goes a long way to explaining the more conservative fossil fuel-based models being proposed [5,61], in which there is a large growth of renewables proposed, but when the growth of overall demand is factored in, not a very large share of energy production coming from them in 2035.

The end result of this scenario would amount to poor prospects for wind power being a clean energy solution for the future, since by 2035, much developing world industrialization will have already occurred, and irreversible damage to the climate will already have taken place. The challenge is therefore for the Wind Power industry to somehow find a way through these barriers. High net worth philanthropists may be a starting point, and shifting production from the west to these countries and investing long term in their community, such that Wind Power becomes their project too, may be another.

In relation to this, these markets will bring new challenges and the need for adaption. For example developing country governments are often adamant that infrastructure projects will stimulate the local economy through having local labour content, and parts content where possible, such that for example the poles can be made locally, and local people can be trained and acquire new skills. The dominant paradigm when dealing with developing countries is now cross border investment, as opposed to simply selling product. Wind energy companies have tended to sell a product and use their own highly experienced and efficient installation and maintenance teams when dealing with installations in the west, so rapid and deep adaption will be required when moving into developing countries.

In terms of market, the modelling of the International Energy Agency regarding China's electricity demand alone over the period to 2035 is that it will be greater than current electricity demand in the United States and Japan combined [61]. In order to supply this unprecedented growth in demand with new manufacturing capacity, while adapting structurally, while developing targeted products for the new market and so on, wind power needs unprecedented investment and long term policy support to scale up appropriately.

Herein lies the challenge, because right now there are emerging factors in the fossil fuel energy market that have begun to drastically sap investment from the wind power industry, just as it was in the process of scaling up its production to meet growing demand in the US, and then the world. This factor (together with policy issues discussed later) has hit the wind industry hard. What needs to be determined now is whether this blow was just a stun, or whether it was a more of a knockout.

5. The challenge of the fossil fuel energy market

After consecutive rises in the three previous years, in 2011–12 in the US, investment in clean energy suddenly fell by 32%, the bulk of which was in the wind power sector [62], and this happened even as installed wind energy capacity in the US grew by 100% (Fig. 9). When investment suddenly sank, it led to the supply of wind turbines becoming double the demand [62] To bring the situation right up to date, wind energy investment had already fallen by a further 17% in the first four months of 2013 [52], so on that basis it is already more than just a one-year period of instability. Many wind companies have been reporting substantially negative annualized returns on investment because of their current price pressures among other factors. Meanwhile, investment in fossil fuel has started to rise again, after having plateaued out in previous years [62].

Many, if not all of these effects are in some way connected the remarkable recent success of the “fracking” method for extracting natural gas (Coal Seam Gas, or CSG) in the US in recent years, which has brought excellent production rates from regions formerly thought to be uneconomic or low yield. It has also been bringing a major turnaround in America‘s terms of trade, economic performance and energy security, so the lobbyists of this gas revolution hold great policy sway.

Regarding the impact on the Wind Power sector, some companies are still bleeding, but some major ones (such as Gamesa) that were in trouble last year, and laid off many staff, also seem to have turned the corner in the first quarter of this year [54] by looking to developing country markets, in their case in South America.

To respond to the challenge of gas and a very difficult 2012, the wind industry has firstly had to do the ugly but necessary business of laying off large numbers of workers, and restructuring to become more lean, efficient and agile. Secondly, it has been responding through reinventing itself. Manufacturing companies that previously sold systems by Megawatt capacity have been transforming into energy service providers selling energy by the megawatt hour, while also taking on more of the long term servicing and maintenance requirements. This has enabled them to have a stable, long term, gradually increasing portion of their income stream as turbine prices fell due to competition [52].

Thirdly, they have been seeking direct investment from high net worth individuals and companies with an environmental ethos. For example, Gary Demasi, director of operations at Google considers renewable energy such as wind “a necessary component” in

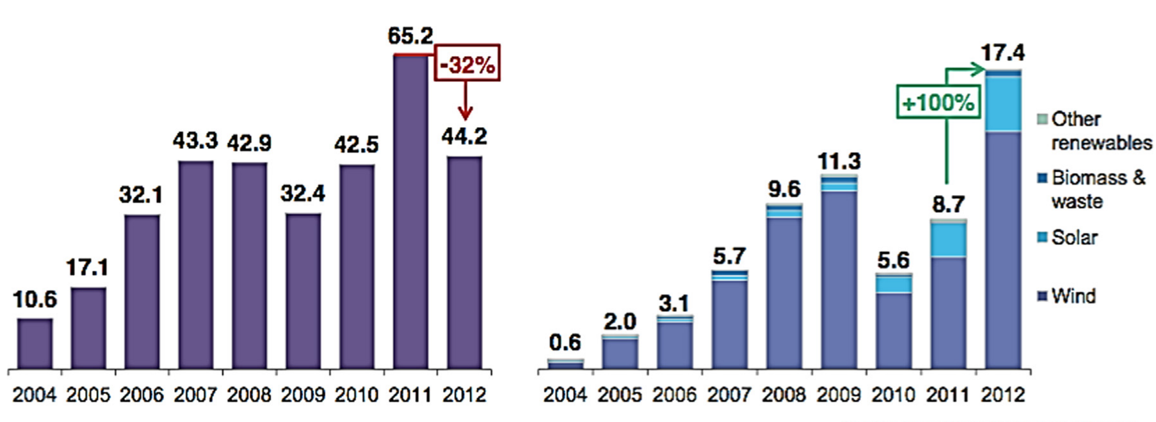

Fig. 9. At left, US total clean energy investment (US Billion). At right, US Giga Watts of new capacity additions in clean energy technologies (taken from [62]).

guaranteeing energy supply for their data centres, which are a massive energy market all by themselves. Therefore Google have direct power purchase agreements worth 13% of their demand with wind farms, including an investment in the Atlantic Wind Connection project [54]. Walmart has a goal of achieving 100% renewable energy power—whether sold or procured—by 2020 [54], and is very positive about wind power. Bloomberg New Energy Finance is investing in wind in a big way, with 58% of its portfolio comprised of wind projects [54].

Fourthly, they have decided to appeal to their base—to the 70–75% of Americans who are positive about wind energy [60] as a means to counteract a slick, well-funded campaign by the fossil fuel giants, to talk down their prospects. “The power of many versus the power of money!” the new CEO of the American Wind Energy Association (AWEA), Gabriel Alonzo declared at this year‘s National Conference in Chicago [60].

Fifthly, wind energy companies have been diversifying their product, where previously they had more of a “one-size-fits-all” approach. This involves designing specific products for low wind regions, and others for extreme temperatures or winds. For example, the Suzlon S97-2.1 model is designed for higher wind speeds [60], as is a model by Northern Power Systems using a direct drive generator [57]. Meanwhile the Gameza114-2.5 is designed for very low, Class II winds, and yet it increases energy production by 29% and lowers the cost of energy by 10%. GE, Northern Power Systems and Alstom all introduced low wind models too. The Alstom marketing concept is to offer three different interchangeable rotor options to go with a single nacelle design [60]. Many of the best onshore wind sites have already been exploited, so models that target lower quality wind, or winds previously considered too extreme, and yet are still able to extract good power from them are a positive development. As will be described shortly, some exciting innovations have been developed for the offshore market also. Through all of this, the industry has also been continuing its trend towards larger and larger turbines, so as to make the technology more and more efficient and cost effective in comparison to fossil fuels, through accessing higher winds at higher altitudes.

The impression in the wind industry as a whole is that after a slow first half of 2013, some solid orders are now in the pipeline for the end of the year, and therefore some predict that next year will be better. But weighing against this recovery are issues to do with policy instability.

Faith Birol, the head economist of the IEC said earlier this year that: “the world of energy is facing a period of unprecedented uncertainty” [62]. The future potential of wind will be decided by how investors respond in the coming few years, both in developed and developing countries, and it seems that this in turn will be decided by who wins the argument regarding the virtues and investment potential of natural gas, and its associated infrastructure, versus that of renewables such as wind, and the infrastructure needed to support them.

The wind power industry has shown itself to be quite resilient so far. Policy positions taken in India this year regarding the promotion and facilitation of large scale offshore wind projects [63], and recently in Uruguay onshore (100% renewables by 2030, 30% from wind) bode well for Wind Power being able to weather the storm of shale gas in the US through seeking investment and growth in developing / non OECD nations such as these.

However, despite all of this, a serious issue remains for the wind power industry to properly address. This is the social acceptability of onshore wind turbines, the current mainstay of the industry.

6. The challenge of social acceptability of on-shore wind power

It has to be admitted that wind power has a serious social acceptability challenge to address, which does have the potential to turn public, and then political sentiment against the technology. These social acceptability issues will now be listed and assessed below, together with the industry‘s response.

6.1. Scale and aesthetic impact on the landscape

One aspect of modern industrial wind turbines that seems very hard to get around is that they are big and getting bigger (Fig. 10). Many current models have blade diameters of around 100–125 m [54], and models recently developed have diameters around160 m. Such installations can completely dwarf the local landscape, especially when multiple turbines are installed in an area. Surveys have revealed that this can sometimes be considered the most important negative impact of wind turbines on a local community. Aesthetic subjectivity may come into this equation, since a distance they can be considered beautiful, even enhancing of the vista by some, while being considered ugly and destructive of it by others, especially those in the local community. Likewise they can be seen as a potential attraction to some, and a complete turn off to others- one that threatens property values and in many cases family health and quality of life [64].

Technically and also from a cost a point of view, unless there is a major unexpected breakthrough, the wind industry has little choice but to make bigger turbines accessing higher level winds, because only by doing so can they compete with fossil fuels on a cost basis. It has been previously thought that it was not necessarily the case that they will continue to grow in size at the current rate, as there are seemingly hard realities to do with dimensional

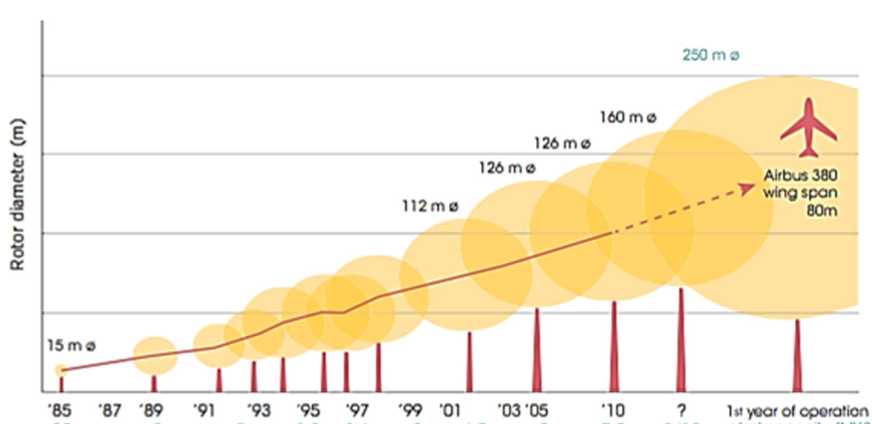

Fig. 10. The increase in scale of modern industrial wind turbines (taken from [54]).

limitations in road and rail transport of pole sections, crane sizes that can lift them and so on [55]. However, innovation in logistics is being used to overcome these limits too [55].

For example, GE has been developing a lighter-weight space frame pole, covered with architectural fabric [54]. This will allow larger, taller towers to be constructed using smaller pieces, which can be more easily transported on the road network and assembled on site.

Another response has been, as mentioned briefly, to look more to offshore wind farms, where scale doesn't matter as much because people are not living close enough to them to see them up close or be annoyed by them. Visual impact issues may be viewed in hindsight as a matter of society acclimatizing to a new reality, as we did with electric transmission poles. And within the bigger picture of climate change, it may be seen as a worthy transition.

Increasing scale improves efficiency and cost effectiveness, but it can have an important detriment too, which is increased noise.

6.2. Noise

After decades of steadily reducing noise in wind turbines through better sound insulation, quieter gearboxes and generators, through switching to the upwind format and making improvements to aerodynamics —some of this work has been undone again through the increasing scale of modern wind turbines. The average noise output at the rotor has been averaging around 105 db for many models recently [65] but the largest models coming onto the market have now broken that sound barrier, going up to 110 dbA in 10 m/s winds [66], gradually edging back towards the high points achieved in the 1980s with downwind models

By far the most important source of noise these days is aerodynamic in origin [67] namely trailing edge noise, tip noise and blade inflow noise.

Trailing edge and tip noise have been a persistent issue for wind turbines over the years, due to the complex nature of the airflow patterns over the blades, which are affected by relative air velocity over the blade, the thickness of the boundary layer and the length of the span at low wind speeds among other factors. At higher speeds the flow patterns change (Fig. 11) due to boundary layer separation and a combination of centrifugal and Coriolis forces acting on the air [68]. The sound generation becomes more complex, since it then involves the interaction of span-wise and chord wise flow in the tip region [69] making the design of this region important.

The most annoying periodic, high frequency swishing or swooshing noise predominantly comes from the trailing edge region near the tip, and also from the tip itself (Fig. 12), [69].

At higher wind speeds, frequencies associated with blade inflow noise become important, as turbulent eddies in the wind of a scale approaching the width of the blade chord use the whole rotor blade surface as a dipole sound board, generating low frequency sound (Fig. 13), [69]. The interactions between blade and pole in each pass of a rotor may also contribute to this and some infrasound generation may be associated with these mechanisms.

The periodicity of high frequency sound is due to the forward projecting cardioid pattern of this sound (Fig. 14), [70]. Much of the noise is produced at the sharp edges of the tip near the trailing edge through the presence of a sharp impedance change for the flow, between the solid form of the airfoil and free space just beyond it [71]. Surface roughness also contributes to sound generation indicating that blades soiled by accretions of dead bugs etc. may be expected to become noisier.

These issues are being addressed through a number of approaches. The first is to reduce the impedance mismatch in the trailing edge region near the tip by installing synthetic brushes or serrations that soften the impedance transition (Fig. 15), [71] Ceramic foam edges have also been used according to the same principle [71].

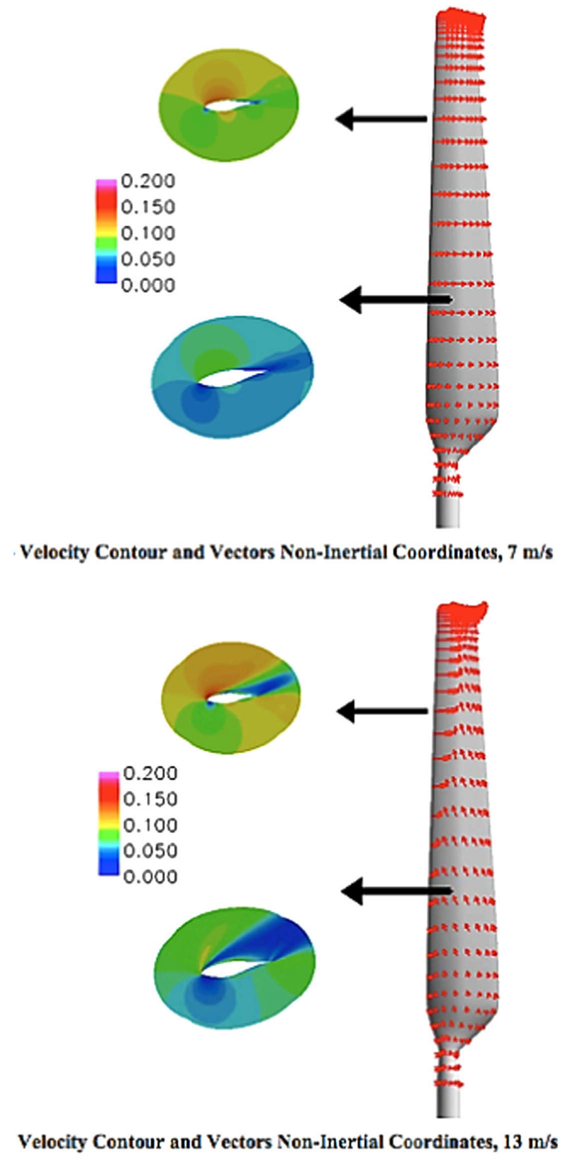

Fig. 11. The change in flow pattern due to boundary layer separation at higher wind speeds (taken from [69]).

Another approach, as used by Enercon Pty Ltd (Fig. 16), [72] has been to modify the tip in such a way that the tip vortex is shed at an angle. This approach may be related to that used in wingtip winglets in fixed wing aircraft in which vector combination of the tip vortex with the oncoming air generates a slight rotational thrust, thus taking some sound pressure energy from the tip vortex and converting it into useful work, while also reducing the power in the wake.

Better computer modelling and experimental techniques are required to resolve unsteady structures in the flow over turbine blades, such as "leading edge bubbles" which may generate additional lift/torque when combined with an airflow passing over them and may be related to the phenomena of "dynamic stall" in fixed wing aircraft in which a plane can greatly exceed the angle at which stall normally occurs through continually increasing its angle of attack. These unsteady structures may also be implicated in noise at certain wind speeds, however they are not yet well understood, and the means to control and harness them has not yet been mastered.

Fig. 12. Location of emanation of high frequency swish sound (taken from [69]).

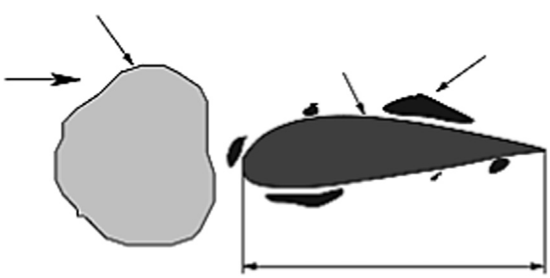

Fig. 13. A turbulent eddy approaching a rotor, causing low frequency sound (taken from [70]).

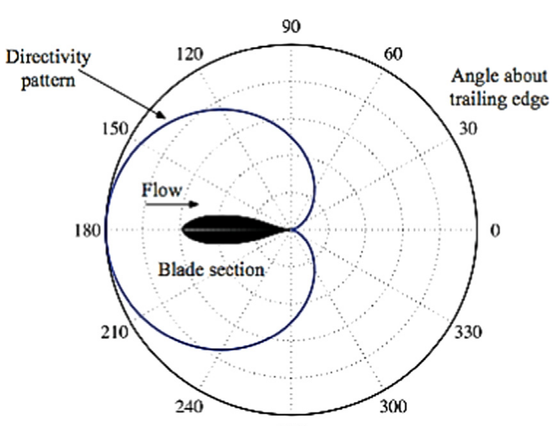

Fig. 14. Forward sound propagation causing periodic sound (taken from [70]).

Fundamental research is being undertaken, as is also urgently needed, to understand wind turbine noise-generating phenomena in a more highly resolved way, both using computer modelling and using experimental procedures. Onshore wind turbines would have less public acceptance issues and smoother siting and commissioning processes if they were substantially less noisy [64]. Clearly offshore models are less affected by noise issues, and can therefore be larger than onshore models [65].

An aspect of wind turbine noise mentioned above as being especially annoying is its periodic nature. Measurements of the impulsivity of the sound are optional [67] so average sound pressures are often taken. When average sound levels are taken over a certain collection time, the high and low amplitudes are eliminated, perhaps resulting in a compliant reading, say below 40 db. But the periodic high amplitude pulse may still be a much higher value and so be clearly audible and annoying [67] especially in a quiet country setting.

6.3. Flickering shadows

Another social acceptability issue affecting onshore wind turbines is the flickering shadows caused, which occur in the afternoon and morning when the sun is low in the sky and shining past a wind turbine. There is a recognized psychological impact of shadow flicker causing serious nuisance in the wider population, and also affecting some epilepsy sufferers [73].

Again, this is a difficult issue for a modern industrial wind turbine in its current manifestation to completely avoid. But it can be managed through careful siting and shadow studies, so as to ensure that any exposure falls within accepted limits.

6.4. Other nuisances and impacts on humans

Wind turbines are now high enough in the sky to require navigation beacons for warning aircraft in the region. These have tended to be extremely bright, and have sometimes annoyed local residents at night. A response has been to use LEDs, which are not as bright in a broad cone as conventional lighting options are, but which still have high visibility over long distances with their narrower cone optics [64].

Another social acceptability factor for onshore wind turbines is the visual impact and annoyance of the new transmission poles and wires required to carry the energy from the wind turbine to the grid. Underground cabling is more expensive, but can be used to address these concerns in many cases [64].

Another factor is the impact on farming land, with rectangular cropping plots shaped suitably for easy planting and reaping divided up into irregular and much less useful triangular shapes by turbine access roads and transmission wires and poles, which can end up taking a noticeable amount of arable land and income from a farm. Earlier involvement of the community at the planning stage regarding the roads and transmission connections would help to address this.

Despite the general approval of wider society with respect to wind power, when it comes to local communities, the negative reactions have often been especially intense, and one of the greatest real costs to the local community. One of the drivers of this has been a fear of property values falling due to proximity to a wind farm, in turn because of the visual impact, noise and other issues mentioned. This can then tend to cause relational problems in local communities because one resident has to agree to land being used for the wind farm, off course for a financial reward, but local neighbours may be affected while not getting any financial reward. This can cause a sense of inequity in the community, and lead to bitter divisions. In this context, any detriments, whether real and medical or subjectively perceived, may also become amplified. The annoyance due to noise and vibration has, in some recently publicized cases, been great enough that several affected families in a region have felt compelled to move from their homes to get away from them. Lower winds generally cause lower noise, so models designed for making the most of low winds may be preferred in this respect.

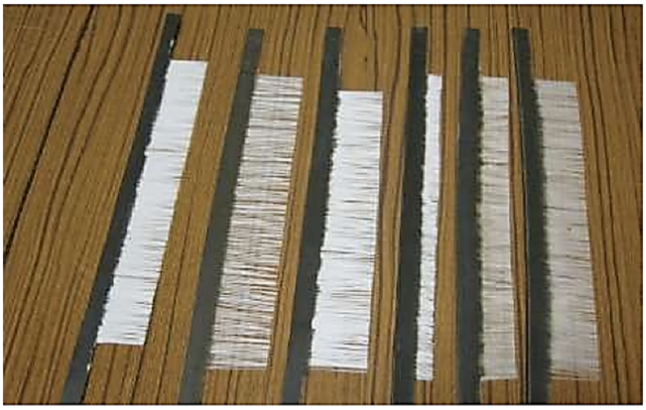

Fig. 15. Polypropylene brushes for reducing noise (taken from [71]).

Fig. 16. Enercon rotor blade tip (taken from [72]).

6.5. *Impacts on fauna*

Another difficult issue to address is the death of fauna caused by wind turbines. Relatively few birds of prey have been killed through hitting/being hit by the blades, but fatalities do occur, and more often in regions used by these birds for hunting, such as mountain ridges and associated thermals, which of course also make good sites for wind turbines. Overall, fewer than 14 birds are killed per MW of installed capacity per year, and often fewer than 4 are killed [74] The birds killed most often are songbirds. Sometimes flocks of birds have flown across the blades and some birds been hit. Small migratory bats are affected—mainly killed by contact, but also by the pressure differences due to the tip vortices which are thought to induce barotrauma. Ground birds such as grouse have sometimes cleared out of an area where wind turbines were located [74].

One innovative solution to the problem of migratory bird and bat deaths has been the tracking of these such that the turbine can be turned off when they are due to fly past [74]. Apart from this, experiments are being undertaken regarding using brightly coloured sections of rotors.

Using some night time lighting of some wind turbines within an array has been considered also [74] since bats strike them at night. There is no silver bullet for dealing with these social acceptability concerns that will work in every case, but the wind industry is developing best practice guidelines [64] that can minimize these issues as much as possible. One is to involve as many people in the community as possible, right from the early stages, rather than designing everything according to technical merit alone, and then bringing it to the community to rubber stamp [64]. Another approach is to offer compensation to neighbours as well as to the landowners who site the turbines on their land. Careful, independent studies regarding noise levels, glare, flicker and vibration are also recommended, with a mutually appointed neutral person involved in mediating between the wind company and the local community [64].

7. The of challenges cost, technical and climate change of off-shore wind power

Offshore wind turbines have become an attractive option because of the higher and more consistent wind speeds available and also as mentioned because they lack the exposure to local community negativity with onshore systems, which delays these projects. But offshore wind farms do have significant cost challenges, and they also face a measure of uncertainty regarding their survival in cyclones, especially the most severe (Category 4 and 5) ones. This would be especially the case if these weather events were to become more prevalent as a result of climate change.

Offshore wind turbines also have some technical challenges to do with reliability in a corrosive environment, along with the obvious issues associated with maintenance access and operation in an ocean setting. The difficulty, not to mention danger of lifting 100 t parts and locating them exactly when the crane is mounted on a listing ship on the ocean, buffeted by waves and wind is obvious, therefore weather-related delays and costs from unavoidable mishaps are implicit. But new designs are addressing some of these factors. These issues will be addressed in turn, along with some emerging possibilities for overcoming them.

7.1. *Cost*

According to the IEA [50] the electricity production costs for offshore wind will fall throughout their outlook period to 2035, but will still remain well above a competitive level. An average offshore wind farm is, at this point, around 2.75 times more expensive than an average onshore system [4], depending on the region. The ongoing operation and maintenance cost of offshore systems is often significantly more also, with the lowest possible offshore maintenance cost being around the level of the highest possible for an onshore system, and the highest offshore costs being close to double the highest onshore O&M costs [65].

However better capacity factors are available offshore [65]. The increased costs are mainly related to balance of system items such as foundations, logistics etc. [65]. Therefore there is great potential for attaining lower cost of electricity offshore if these issues can be addressed through innovation.

7.2. *Technical innovation*

Despite some attractive aspects, without technical breakthroughs, offshore wind farms have a long road to parity with fossil fuels. To address this, substantially larger offshore models [66] designed for installation and operation at sea, and to reduce installation time and maintenance frequency—are being developed and prototyped by Siemens, Vestas, Gamesa, GE and others. These improvements, along with the experience curve concerning logistics, installation and maintenance, are expected to bring incremental cost and profitability improvements over time, however a game changing improvement would seem to be required to truly unlock the potential of offshore wind power.

Perhaps one such transformative concept is floating offshore wind turbines [75] (Fig. 17). This concept has the huge advantage that the installation could happen on dry land, and then the

floating wind turbine be dragged out to location and hooked up in various ways to the seabed. Likewise any serious maintenance could be done on dry land if necessary.

Several versions are being proposed including a stand-alone version with a wind turbine buoy extending down from the pole, a triangular pontoon with floats on each corner and the turbine on one corner, and a ~500 m long pontoon carrying 24–30 wind turbines.

A Japanese version of the latter is being developed (Fig. 18) [76] which has an added innovation—a nozzle shroud around the rotors, which has the effect of greatly increasing wind velocity and power production.

Using a floating system would be aimed at reducing the balance of system cost for offshore wind turbines, and even more importantly, giving wind turbines access to deep water regions with higher winds (Fig. 19). It may also reduce the possible environmental impact of the large undersea steel / concrete foundations used presently.

Crucially, it seems also to finally solve the social acceptance issues of noise and visual impact experienced onshore, and to some extent experienced close to the shore in shallow water. It may also offer some flexibility, such as may be needed if wind patterns change in the future as a result of climate change. This concept would potentially enable the wind farm to up and move to a new location, or change its angle of orientation as required.

This last point brings up the important issue of how climate change might especially impact the offshore wind industry (but also the onshore wind industry in different ways) over coming decades.

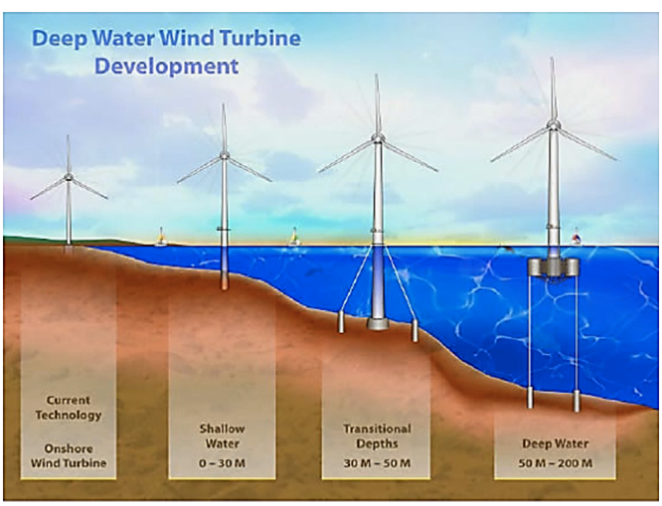

Fig. 17. The progressive development of wind technology out into the ocean (taken from [75]).

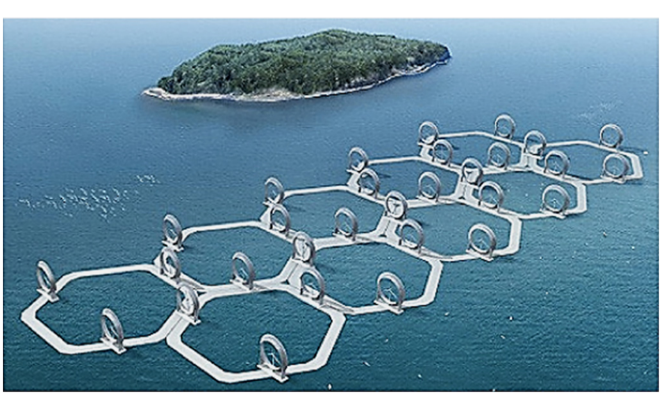

Fig. 18. Japanese floating pontoon wind turbines with "wind lens" nozzle shrouds (taken from [76]).

7.3. Climate change

Approximately 88% of offshore wind potential must be exploited in cyclone risky regions [77] Therefore one of the challenges for offshore wind Power is the possibility of turbines facing a category 4 or 5 hurricane or cyclone. Existing wind turbine models have endured Hurricane Sandy, (a factor 3 hurricane), without failure, but appears to have been an increasing frequencies of severe cyclone events in recent years which peaked over oceans at factor 5, such as Yasi in Australia and Katrina in America. IPPC modelling is consistent with this, suggesting global warming (Fig. 20) will cause a decreased tropical cyclone frequency, but an increase the severity of the worst cyclones.

For this reason some reports have suggested that half of the wind turbines proposed for ocean regions off the US east coast might be destroyed within 20 years by hurricanes. Therefore the issue of the impact of cyclones on wind turbine sites must be considered. Designing turbines to handle 60 m/s winds instead of 50 m/s (the standard value) would result in a 20–30% higher cost of turbines. In another study, required upgrades would amount to adding $A42/MWh to the LCOE [77]. It is unclear as to whether wind turbines would find a market at this price; therefore, this is an area that requires a technical/cost breakthrough.

Changing wind patterns as a result of Climate change are also crucial. One 2007 study has shown a relatively high probability of decreasing wind strength across Australia in the period up to 2070 (Fig. 21), and also significant changes in regional wind patterns [78]. Another study also indicated a slowdown in Pacific winds over the last six decades, and changing wind patterns. A 2005 study regarding northern Europe predicted an increase in wind density as a result of climate change, and also a shifting of wind patterns such that easterly winds occurred less and south westerly winds more [79] However a 2012 study contradicted this by suggesting a 2–6% reduction in average wind potential in Europe in the period up to 2049 [80].

Having predictable wind patterns is important for the wind industry, as industrial wind turbines are a major investment, and a project's viability depends on solid forecasts. This may be a reason for the industry to consider floating wind turbines, or other similar concepts that are more flexible in deployment.

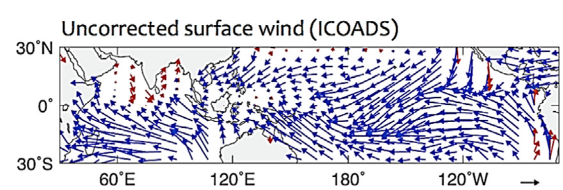

Fig. 19. Pacific Ocean trade winds (taken from [52]).

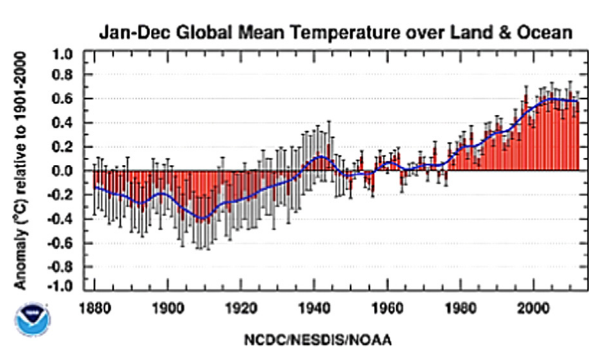

Fig. 20. Global warming over last century (taken from [77]).

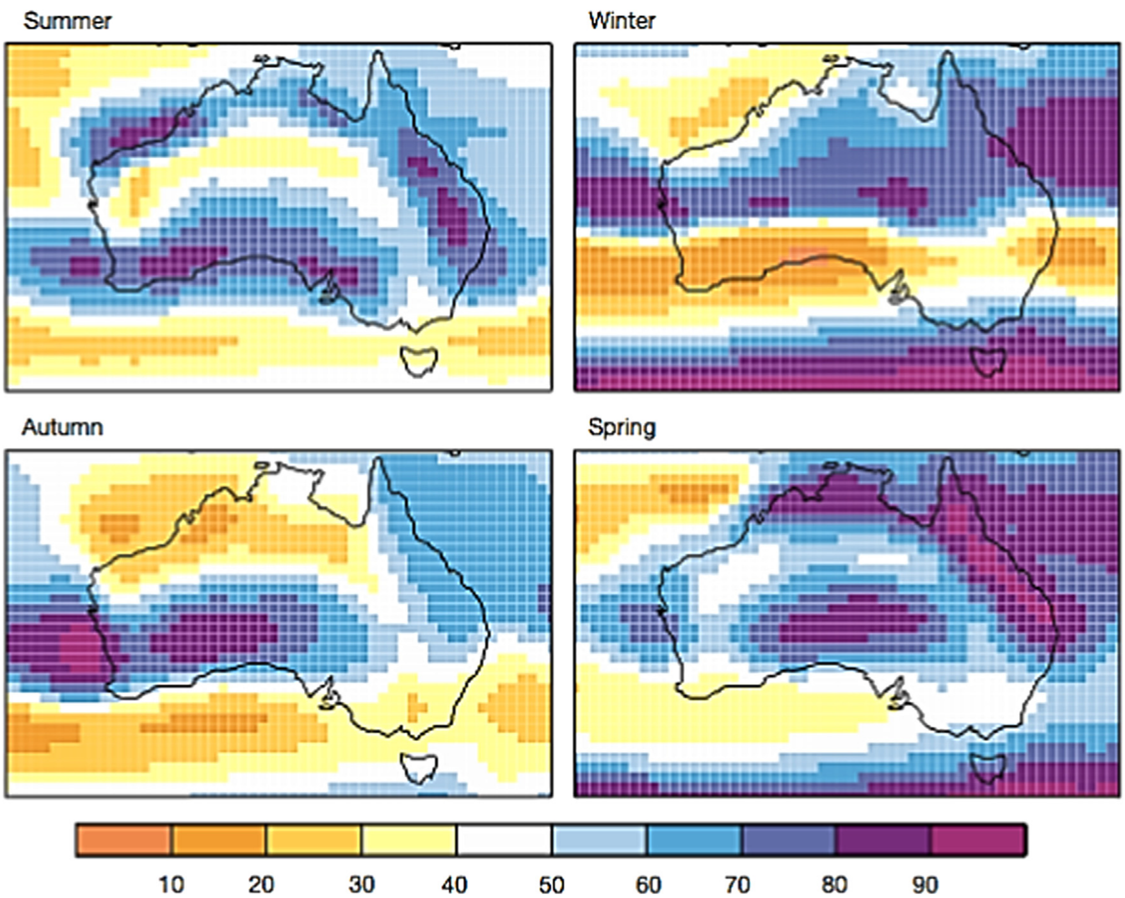

Fig. 21. Risk (probability in %) that wind speed will decrease in 2070 for summer, autumn, winter and spring (taken from [78]).

8. The challenge of competition from other clean energy competitors

Wind power will face growing competition from other renewable energy technologies over coming decades, especially from solar genres, but also from geothermal and methane/biofuel. Onshore wind is among the very cheapest of all energy forms at the moment however [4], and a single installation can generate power at an industrial scale of multi megawatts (up to 8 presently), making onshore wind financially attractive.

With respect to Wind Power's solar competitors in a developing country like South Africa (Fig. 22) for example, it will take at least a decade before some forms of CSP challenge it, and before solar PV come within range [81]. Citi Research (Citibank) has also offered a comparison between wind and solar cost curves [82].

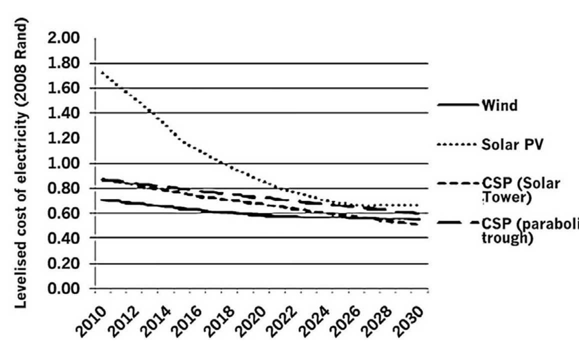

Fig. 22. Cost projections for onshore wind power and various solar technologies (taken from [82]).

Once the different vertical scales are taken into account, these graphs predict that solar PV won't be within striking distance of onshore wind in terms of cost until sometime shortly after 2020, but it should also be noted that solar is dropping in price faster than wind.

In many respects, however, the main different forms of renewable energy are quite complementary. Preference for one or other option is often determined in by the qualities of a given site rather than the cost alone, with solar being appropriate in built up areas and wind in more remote areas, for example. Likewise, with development in coming decades, wave energy will find its ideal locations and so will geothermal, methane and biofuels. If competing with and replacing fossil fuels, there is significant capacity to go around for all forms of renewable energy, but in terms of cost and maturity, wind energy does have a massive head start over most other renewable energy forms apart from hydro, so it is assured a significant place.

In terms of their complementarity, we have seen already how wind power can benefit from the proximate installation of a hydro system, enabling the wind farm to replenish the hydro resource, while the hydro resource provides dispatchable power for the wind resource. Therefore there is little competition between the two in these respects. Industrial scale Wind and PV solar can be seen as competing, but when Solar PV and Wind Power are combined in the electricity grid, there is often a significant degree of complementarity between the two, implying that there is a role for both. For example, in a study in Germany (Fig. 23), it was found that sunny days are more often less windy and windy days generally less sunny, and also sunny months are generally less windy and windy months generally less sunny, such that both

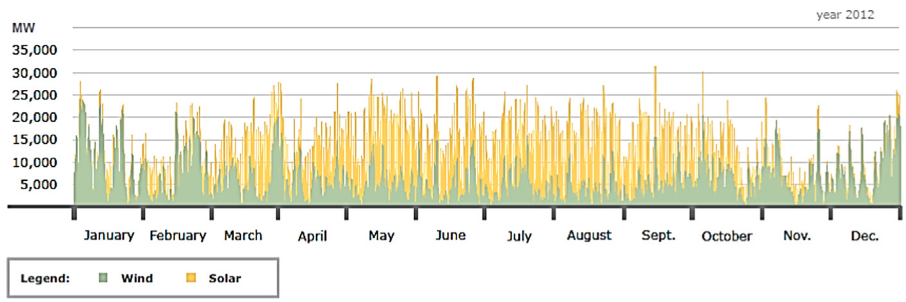

Fig. 23. Wind and solar combined in a grid over a full year (taken from [83]).

together can produce a reasonably consistent supply [83]. Of course this effect would have regional aspects to it, so it would not necessarily always be the case.

Wind power is again cheaper than, but also potentially quite complementary with concentrating solar power (CSP) due to the capability of CSP to provide thermal storage and dispatchable power offering a renewable form of grid balancing, which natural gas may otherwise need to supply. It would also have the capability of removing grid bottlenecks potentially caused by the integration of very variable supplies. Conversely, wind Power would take the pressure off CSP in the less sunny periods, which can tend to be windier as seen above, reducing the need for CSP to use its own gas back up supply.

The emergence of smart, interconnected, international grid would enable these collaborations to deepen, by connecting more distant wind, solar and hydro facilities, and doing so more effectively than before, as will be discussed in the last section.

9. The challenge of policy instability

A common thread in the renewable technology experience over recent years has been the failure of governments to provide the policy stability that would enable investment certainty and growth. A classic example regards the current administration in the US holding the industry in suspense year on year about the future of the production tax credit (PTC). The PTC makes a big difference to the viability of many wind projects [60], and the number of projects that go forward makes a big difference to the number of employees needed by the company, so not knowing puts the industry in a dilemma. What do they do with their staff while they wait to find out?

For example, modelling done by Navigant in 2012 for the American Wind Energy Association (AWEA) indicated the difference it would make for the industry, measured in 2016, if it had 4 years of forward certainty regarding the PTC, compared to, if it ended at the end of 2012. Approximately 45,000 jobs in the American wind industry, worth 8 billion dollars of investment, 45,000 MW of installed capacity and 65 million tons of CO_2 emissions were found to be hanging in the balance. Instead of extending the PTC for 4 years as was requested, the government extended it for only one year, doing so late in the year, and applying only to projects beginning production in 2013. It was a welcome relief for some—at least a stay of execution, but it came too late in the year for others such as Vestas, because of the time required to get projects to the production stage, leading to 2013 being another flat year for them [84]. By contrast, the US government has made an executive order to fully exploit its unconventional gas reserves in coming years and to support that industry, involving long term planning [85], just as the US government has supported the fossil fuel industry with tax credits and other subsidies for over 100 years now.

The wind industry has been responding to this by increasing its lobbying power, firstly by employing more people in its industry group, the AWEA [86]. It also chose a chairman overseeing all of this who had been a lobbyist for the oil industry previously, so he knew how things operated in the Whitehouse. Through this they were able to organize sending delegations of representatives from many of its 2000 member companies, taking hundreds of thousands of letters from its constituents, thus beginning to become a lobbying force to be reckoned with in competition with big oil and gas. As a result, the PTC was extended, if only for a year [86]. But the threat was that it would not be extended at all.

In other countries such as Australia, cap and trade emissions trading scheme legislation has been brought in which has offered a longer-term and more deeply embedded support for the industry.

10. The challenge for the world—CSG or a smart grid of wind and other renewables?

Current energy investment movements can broadly either go towards CSG and the conventional energy architecture, or towards renewables such as wind and the smart grid. Now we will investigate the two options, starting with analysing CSG as a bridge to a clean energy future.

10.1. CSG as a transition fuel to a clean energy future

One of the main arguments for GSG being a transition fuel to a cleaner energy economy is that it releases around half the CO_2 of an average coal-fired plant, and vastly less particulates over the lifecycle of a plant, plus it also has a reduction in some other pollutants [86]. So on that basis gas is around twice as clean as coal. However a question remains as to whether investing in gas production, and thereby increasing its volume supply to the market, and so decreasing its cost would actually result in a reduction in CO_2 emissions. Factors beyond simply the CO_2 emissions of gas itself need to be considered.

As is widely known, many countries in Europe are in a debt crisis presently. Therefore some have been forced to rescind many of their best environmental intentions, and yet they are already thoroughly industrialized nations with a heavy dependence on electricity. So when gas becomes cheap in the US and is used domestically, forcing US coal to become much cheaper and be sold offshore, at a time when the price of conventional gas is high in other countries (Fig. 24), a debt-stressed European nation may see no option but to buy the cheap coal and adopt more coal-fired generation. This may result in switching from a cleaner energy source like conventional natural gas, to a dirtier one like coal, and that is exactly what has happened, as mentioned by the IEA [1].

The fact that coal is being exported and sold in greater quantities doesn‘t necessarily mean that the coal industry is unaffected by CSG—there are indeed reports of high margin pressures, mass layoffs and mine closures in the coal industry, in many places globally. Cheap

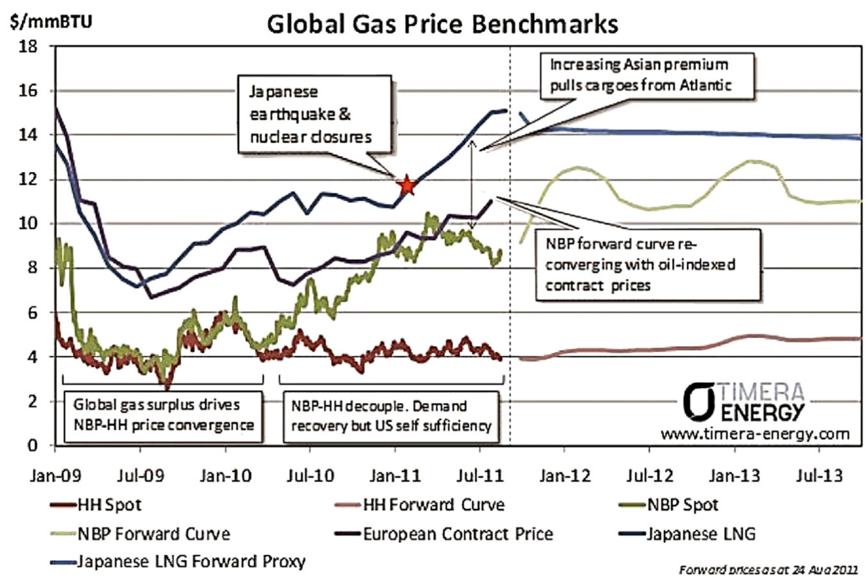

Fig. 24. Global gas prices (source: Timera energy). HH is the US shale price.

CSG is mentioned as a key reason for this, along with increased regulation and some other factors, and the difficulty is not short term. If there were not a series of populous developing countries lining up for cheap energy to industrialize, then the impact may have been to substantially end coal production, but as it stands the impact has been to shift coal-fired energy production to the developing world and to western counties that can't afford gas, which is not really an outcome that is in line with the “transition to a clean energy economy” ideal.

But there are some counter arguments proposed in favour of CSG as a transition fuel. The IEA offers modelling indicating that that exploiting less shale gas would have the perverse effect of increasing energy-related CO_2 emissions by 1.3%, [87] since more coal would be utilized instead.

However the same IEA, but on page 8 of a different report: “Tracking Clean Energy Progress, 2013”[1] admits as mentioned that the boom in gas in the US had the opposite effect in Europe, driving them to use more coal at the expense of gas. It is not clear in principle why it would not have the same effect in many places elsewhere in the world too as we have suggested. In fact this same report notes that coal has recently increased its share of total energy expenditure, and done so faster than other energy sources, and crucially, done so mainly in developing countries [1]. So the conclusion that they too have been negatively influenced by cheap CSG in the US to buy cheap US coal exports seems plausible.

A more sophisticated “middle ground” argument regarding CSG and renewable futures, that appears to hold some weight has been made by Citi Research [88], to the effect that the proclaimed “golden age of gas” will not necessarily be to the exclusion of renewables, and won't necessarily divert investment away from them, because they are actually co-dependent. Interestingly their analysis backs up the comments made so far about the impact of low gas prices in the US on the price of coal elsewhere—suggesting that in the short term, despite being so much cheaper than conventional gas, shale gas will be priced out of the conventional market overseas, and by this they clearly mean because of cheap coal, since crude oil prices have remained quite high, and aren‘t relevant to electricity generation anyway. Therefore the conventional market has moved towards cheap coal and even cheap CSG can‘t compete with it outside of the US, so it needs a market facilitator, namely renewables.

They suggest that CSG will need renewables in order to find a market in the short term, since gas will be required for balancing renewable energy‘s variable supply until smart grids become available—and also until forms of renewables with storage capability such as solar thermal become mature and price competitive. In the meantime, variable sources like solar and wind will need CSG in order to balance their supply to the grid. Their vision is essentially that renewables and CSG will be locked in a polite, if slightly awkward embrace, keeping up the appearances of mutual affection until renewable energy can finally muster the strength to dump gas once and for all, and move on to its true love, the continent-wide “smart grid”.

They also make the astute observation that the price of CSG is very uncertain, and that by the time it is exploited in markets other than the US, it is likely to be much more expensive than renewables, so its long-term, if not medium-term investment prospects may be poor.

There is a question hanging over this concept, since some suggest that gas turbines are not really designed to ramp up and down in output to the extent required to balance the wide variations involved, in fact that they become very inefficient when used in that way [2]. In other words, used like this they don‘t end up saving so much CO_2 in comparison with coal after all. But despite this, it has to be admitted that the Citi Researchers do have a point—in the short term it is likely that renewable energy will need some gas generation for balancing purposes, even if it is inefficient when used in this way.

They go on to quote some expert opinions about the future of the shale gas price, and it doesn't bode very well. While the current shale gas price is about 4 MMBtu (Fig. 26), and the futures market has it falling slightly over the next 5 years, these analysts mention studies suggesting that even in the US, much of the resource is uneconomic to extract below $5/MMBtu, and that according to some studies, this portion can‘t be extracted for much below $6–8MMBtu. And yet, as they say, wind power would already be competitive with shale gas at $6/MMBtu.

If they are right about these assessments, then there may be a ticking time bomb under the US gas market concerning the point at which the really cheap gas runs out, and the pipes begin to flow with the more expensive gas. But having said this, it is also

possible that further innovation could save the day and improve the yield yet further, leading to an even lower price. But then against this, it could happen that some catastrophe will cause greater community resistance such that the government will force tighter regulations and restrictions, with their associated increased costs. At worst, a serious contamination of aquifers and drinking water could bring the whole industry to a grinding halt. At that point its former benefit to US national interests and terms of trade, and its powerful lobby influence may be overwhelmed by public outrage. So really, anything could happen.

While some points are agreed, one thing that can be said against the Citi Researcher‘s argument is that there is no doubt about whether CSG will divert investment away from renewables, because it already has—massively. Quite a number of prominent wind energy companies are now in financial dire straits [54]—precisely because of a divestment from them to CSG gas. So this fact, in turn, brings into question another aspect of the Citi Researcher‘s argument. If the survival of CSG depends on renewables such as wind, and yet the survival of core players in the wind industry is mortally threatened by the rush of investment in CSG, then aren‘t those investing in CSG and abandoning wind destroying a key enabler of their own investment, and sabotaging their own market?

When the Citi Research analysts admit that renewables will no longer need gas when the smart grid comes, they are also conceding that the gas-fired generation infrastructure that is being invested in now will be largely abandoned at that point. It may seem for many to make more economic sense to invest in infrastructure that will be in place for at least 20 years, namely in renewable infrastructure such as wind turbines and the smart grid.

So if on at least two solid economic grounds the future of CSG seems weak, one might ask if there is a good environmental case for it instead. But this should also be analysed, especially with respect to fugitive emissions.

The way CSG extraction works is that drilling is done in a curved or diagonal path, and enormous water pressure is applied along with sand and chemicals, and the result is that hard, oily rocks fracture and release natural gas into the well [89]. The main component of natural gas, methane, is collected from hundreds of these drilled and “fracked” gas wells, each with a valve on top. Some of the ground around the site may have been imperceptibly changed however, such that methane can escape through the ground surface, as evidenced by rising bubbles of methane appearing in streams and mud. But this loss is difficult to measure and assess, since it can happen over a huge area and be affected by geological features beneath. However a UNEP alert report has mentioned that increased air pollution around CSG wells was found to be systematic, and that aromatic poisons used in the process had contaminated the local populations. For example Toluene was found in 65% of people tested, and Xylene in 53%. But only a handful of empirical studies have been done regarding fugitive emissions of Methane, and they have revealed wide variations in results. But some of the most thorough and credible ones suggest around 4% of Methane produced is lost in fugitive emission [90]. This figure is much higher than the value calculated by the industry's formula-based estimating method. Overall this situation shows how little hard empirical data has been gained by the industry [91]. It is therefore quite hard to fathom how industry representatives and others could confidently assert that CSG is necessarily cleaner than coal and therefore some kind of transition fuel or bridge away from the dirtiness of coal-fired power generation, to a cleaner energy future.

The gas produced in CSG wells commonly has too high a content of CO_2 in it (around 11% has been reported) so after transport to a processing plant, this CO_2 is removed and often vented to the atmosphere, so that is one major source of fugitive emissions.

Venting of the 10% proportion of CO_2 in a shale gas resource led to making it 10% harder to reach the emissions target for 2020 in a Canadian example [89]. Then there are fugitive emissions of methane and other components from compressors a condensate storage tanks and process flares, which when measured have been found to be 5–7 times higher than the levels calculated by industry formulas. Other studies have also indicated that Methane from natural gas emissions contributes 44% of all US Greenhouse gas emissions and warming effect at the 20 year time scale including all CO_2 emitted in US [91]. It was also found that fracking produces 40–60% more methane emissions than standard techniques. Fugitive emissions could represent 3.6–7.9% of Methane production due to the fracking process [91], which would potentially make CSG-fired power an even dirtier process than coal fired generation. This is because methane is a very powerful greenhouse gas, even at moderate concentrations, newer research revealing it has 33 times the warming effect of CO_2 [91], and over a100 year duration.

However it should also be noted that a later MIT study [90] suggested that if extraction companies use gas flaring or—green completion‖ techniques instead of venting, then the emissions can be 4-5 times lower, and they then found, through talking with industry representatives, that such techniques were already being used in approximately 70% of cases. However no empirical data was gained to verify this. Gas flaring burns the Methane and converts it to CO_2, so the claimed difference from that component would seem to amount to the difference in warming effect of Methane and CO_2, which is 33 times, but not all of it would be converted. The mention of “Green completions” refers to using a large portable tank to collect gas that would otherwise escape when the pumped fracking fluid comes back up, and this process, allegedly now starting to become more standard, is reported to collect “over 50%” of fugitive emissions. But the balance still escapes it seems [90].

While acknowledging the disputes, anecdotal reports of methane finding its way into domestic water supplies and images of people lighting their faucets, along with the news reports of the widespread death of wildlife and fish in these areas, all points to the conclusion that the immense pressure used (with the pump alone filling a semi-trailer), and the micro-fracturing of hard rocks that occurs, and with all the other processes involved, methane and fracking toxins can be pushed into all kinds of unexpected places, and then ultimately into the atmosphere and drinking water supply.

On the basis of all of this information, it seems difficult to maintain the assessment that CSG—produced as it is in this way, can be considered a transition fuel to a clean energy economy. It would therefore also seem likely that when these facts percolate through the public consciousness, CSG extraction will become more and more difficult and expensive to do, and at that point it may quickly die out.

According to the IEA, (which started out as a body dedicated to fossil fuel cooperation), the emissions embodied in their New Policies Scenario, in which CSG and shale oil are promoted, corresponds to a long-term average global temperature increase of 3.6 °C [61]. For reference, the temperature rise to date, driving the climate changes we have already observed, such as multiple extreme droughts, floods and bush fires and the accelerated melting of the North Pole, has only been 0.74 degrees [92]. The IEA also point out that almost four-fifths of the CO_2 emissions allowable by 2035 under a 2 degree warming scenario are already locked-in by existing power plants, factories, buildings, etc., allowing precious little room for new carbon emitting infrastructure in the developing world in this period. Even more dire is their statement that if no action is taken to reduce CO_2 emissions before 2017, then all the allowable CO_2 emissions would be locked-in by energy infrastructure existing at that time [50].

This statement clearly shows that any delay in switching to an unprecedented investment renewables and their facilitating energy structures, let alone any divestment away from them, is not a viable or responsible option if we want to avoid destructive climate change. 3.6 degrees of warming by 2035 is truly an unimaginable prospect, and an outcome that is not in anyone's interests. So having acknowledged that there is an issue with the variability of renewables at present in relation to grid demand, and yet having also faced the fact that CSG won't solve the global warming issue but more likely make it worse, is there a way forward in which intermittent renewables can be used more effectively in the grid?

10.2. A smart grid of wind and other renewables

A viable alternative to CSG gas as the means to balance the grid is to use renewables across a smart grid. If a grid network is large enough that the demand is different in different regions across the network, perhaps because the time of day is different, and if it is also

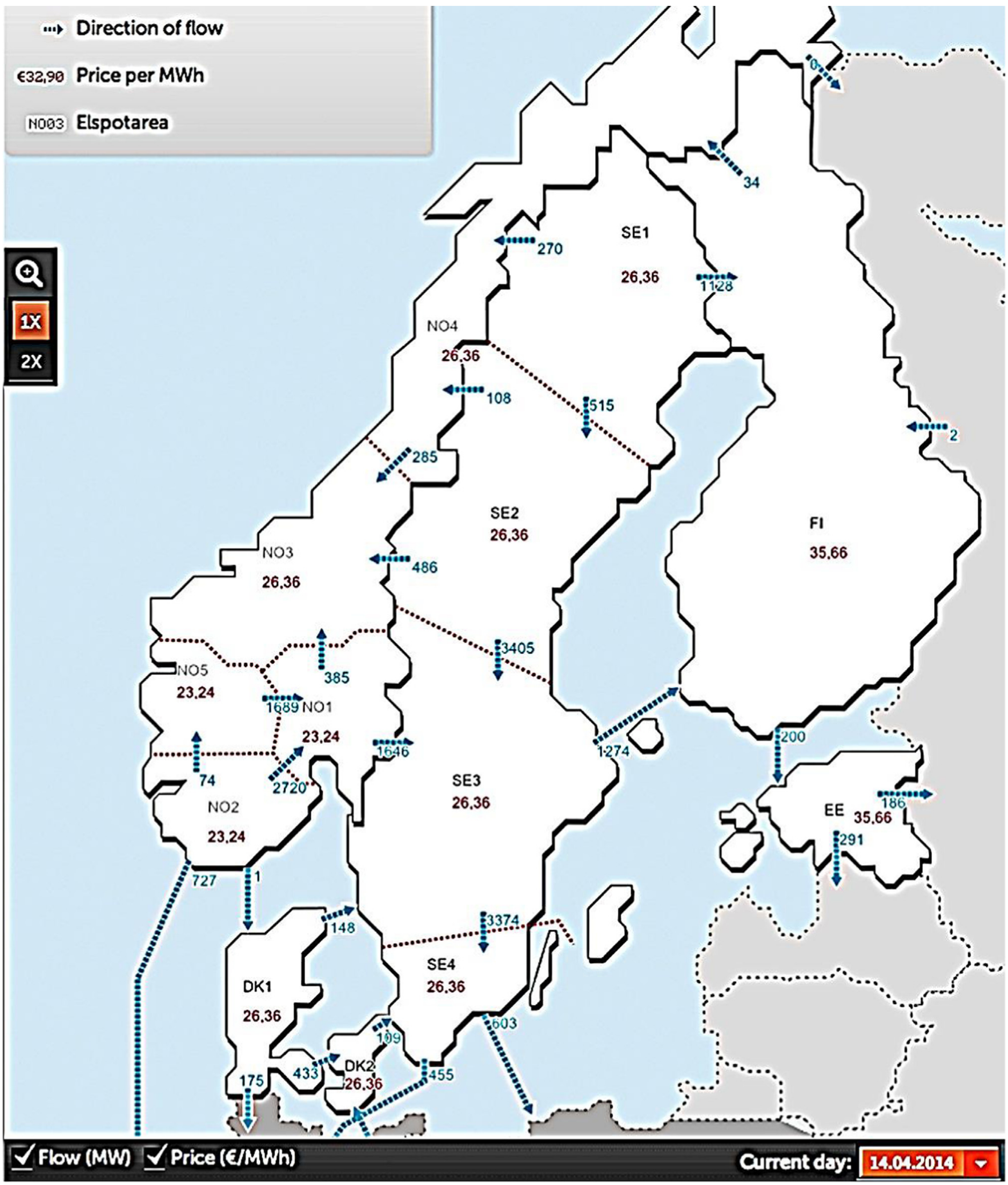

Fig. 25. The integrated Nordic country energy grid system (taken from [93]).

large enough that the weather is different across the network, then the intermittence effect can be handled by a sophisticated, networked energy exchange, using the unique resources of contributing countries to make an effective and consistent energy supply system for all.

Something like this is already being used on a smaller scale in Nordic European countries such as Denmark, Sweden and Norway among others [93] (Fig. 25). To be most effective, the network should really be bigger than this, but they do have the advantage of offshore wind power in Denmark that is quite consistent, and a good hydro system in Norway. As mentioned, this hydro system can be used to store energy by using any excess wind power in Denmark to pump water uphill in Norway. This can then be reclaimed when passing through Norway‘s hydroelectric generator. At present they have a decent percentage of hydro and wind, but also use a higher proportion of nuclear. But they are on track to being powered by 100% renewables within 40 years.

Another example of an emerging smart grid concept is Desertec [94] (Fig. 26), which aims to integrate renewables such as solar and wind placed in deserts and remote areas across the world, with major population centres, via an integrated smart grid.

Yet another regional concept being proposed and developed along similar lines is called Grenatec [95], (Fig. 27), which is seeking to create a smart grid connecting Australia with China and the Southeast Asia/Pacific region. As they mention, the data cables required are already largely in place, or being placed at the moment or soon, associated with national optical cable Internet rollouts. So the main component missing is the large DC (or possibly AC) copper cables needed to connect the nodes and to traverse to other countries across oceans, along with the software and hardware development of the system to control it, and of course the local and international negotiations required to make it all come to fruition.

So how would it work? For example, in one region let‘s say it is around 2 pm, so solar panels are pumping out power, and much more than is needed locally. In another region of the network it is early evening and people are switching on appliances, so this solar power can be sent to them across the network, with renewable voltage support along the way as required. Meanwhile in another region it is later in the evening and the wind is blowing, so this power can also help meet the peak demand somewhere else.

If there is a time in which the whole network has too much power, then it can be used to pump water into a hydro scheme in one region of the network, or a number of mini hydro schemes, ready to generate power in the times when the network as a whole has too little power. Offshore wind would be a mainstay of this system because of its phenomenal output potential and good consistency, especially in deeper water regions. Solar thermal plants located in deserts with storage would also be used to store power for balancing purposes. Intermittence could therefore be removed, through the network using clever weather prediction and supply algorithms to integrate different variable sources across the network such that the supply always meets demand. The grid could also use demand side control of products such as fridges and air conditioners to tweak the balance as needed. Smart meters would be used so that people would be billed appropriately in their home country, even if the power actually came from somewhere else.

Gas pipelines are already shared between nations, so an international energy grid—perhaps the energy equivalent of the "Web" in the world of data, seems entirely possible. Of course it would require a massive investment, but as Warren Buffet has mentioned, the deregulation of the energy sector is actually a very attractive investment opportunity—one of the best ever actually, since it is now allowing individuals to invest in infrastructure that will be used by everyone over many decades or more, such that they can take part in what was once a complete monopoly.

So this kind of connectivity—of sourcing power from a distant place when it is available, seems to be a key enabling component of a true clean energy solution, and this is one in which wind power could take a significant place by virtue of its low cost and mature status. In such a scenario some gas-fired generation may be kept in the earlier period while the knowledge needed to move to 100% renewables is acquired, and a lesser portion may be retained for a longer period as a last resort back up system for certain contingencies, but for the most part, it would not really be needed. To maximize efficiency, local power supply could be prioritized, and if more storage were added to the network, the international/long distance flows would become less.

Now turning our attention back to the original question posed in this section—the choice between CSG and renewables/the smart grid, one important consideration is priority, meaning the order in which things are done. For example, the outcome for the world will not be the same if the transformation to a smart, renewable energy economy is simply delayed for a decade or so, through conventional CSG being given investment priority now. The industrialization of the west has already had a major impact on the climate through the use of fossil fuels, but the industrialization of China, India, Africa, South East Asia, South America and the Middle East, all at approximately the same time, will be devastating if it is mainly powered by fossil fuels, as is forecast by so many. It is by no means certain that a clean energy future for the world would even be possible after that.

For example, in certain polluted industrial regions of China it is widely acknowledged that the sky is constantly smoggy, often being a diffuse brown rather than blue. If the rest of the world industrializes like China, then skies may progressively become polluted, dimmed and almost never clear more broadly, severely limiting renewable technology options, especially solar. As we have seen, climate change may already be reducing wind potential in some regions, while also making it more unpredictable, and also

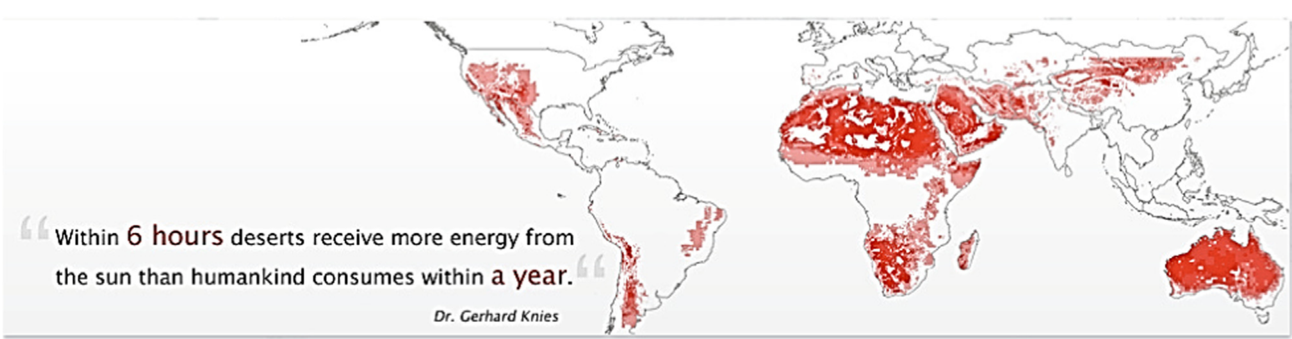

Fig. 26. Desertec—the concept of connecting desert and remote regions of the globe suitable for renewable energy collection with the population centres using large electrical cables (taken from [94]).

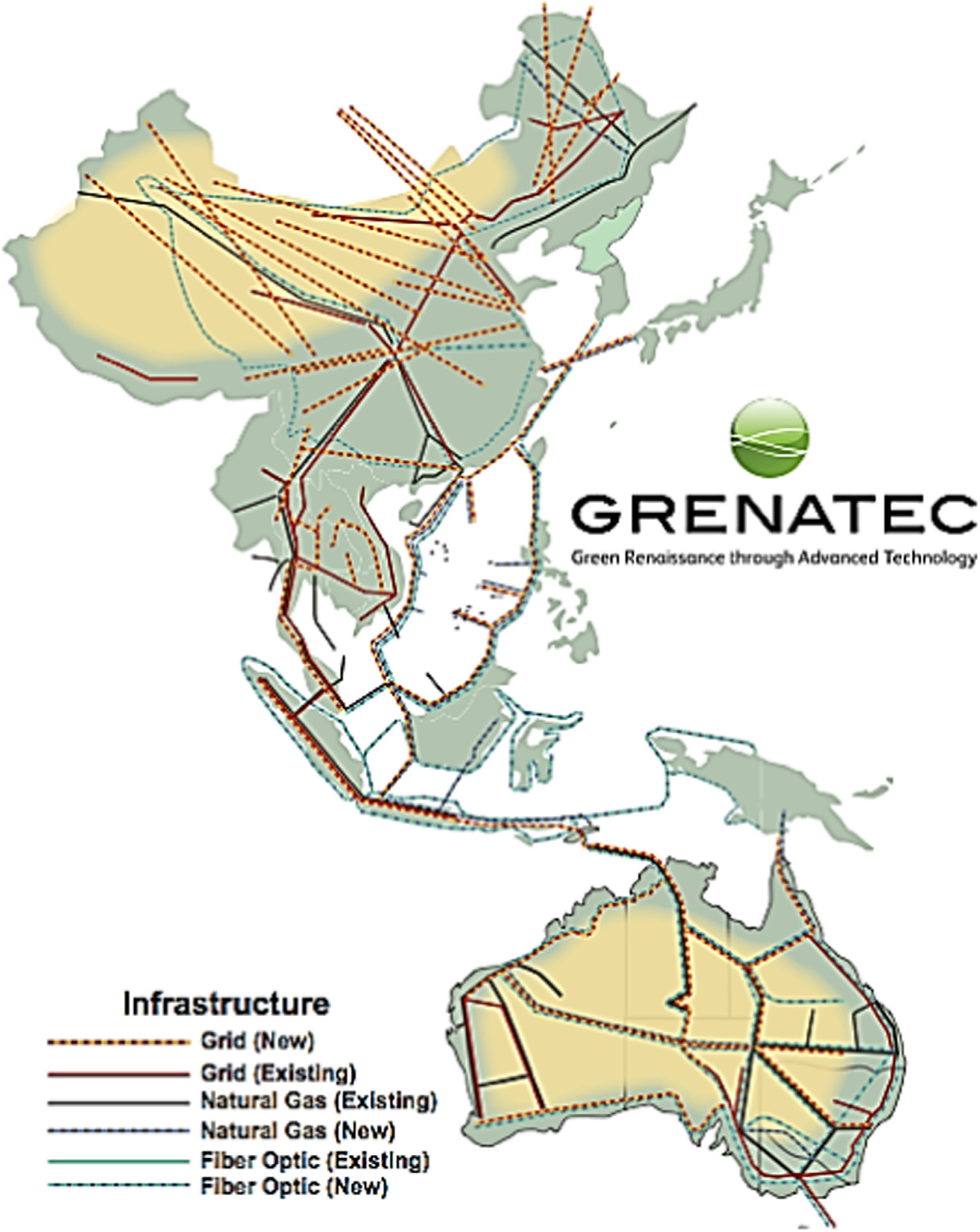

Fig. 27. The Grenatec regional smart grid proposal (taken from [95]).

more damaging when severe cyclones and storms pass through. Lastly, while acknowledging the wonders of human ingenuity, the wonders of its stupidity also need to be taken into account. As temperatures rise, foolhardy geo-engineering schemes—such as already being proposed—may be actually enacted to try to address climate change and warming when it is really too late, such as

artificially dimming the sky (SRM, Solar Radiation Management), potentially putting a complete end to the whole solar industry, and most likely also wind. Therefore, while the chance to bring about a clean energy future still presents itself, it must be taken without delay.

11. Conclusions

In this review it has been seen that wind turbine companies have a challenge to meet regarding declining performance of turbines over time, but this is being actively addressed through improvements to components, doing the maintenance more proactively themselves, and innovations in blade cleaning and drive systems. It was then seen that intermittence of supply has presented difficulties regarding grid integration, but also that the associated costs of doing this are comparatively small at present, and that using more offshore systems would substantially overcome this. However the "constraint" situation needs to be addressed more equitably and transparently. Onshore turbines are also addressing the issue using a small battery and signal smoothing/storage system, but a full solution may require the smart grid.

After this we saw the growing pains caused by the need to expand and access developing world markets and the adaption required in doing this, compounded by the serious challenge posed by cheap US shale gas flooding the market and sapping investment. But we also saw the resilience of the wind industry to adapt by restructuring, looking to high net worth/environmentally focused individuals and companies and diversifying their product range, and that some appear to have turned the corner. Then we saw how the wind industry is tackling social acceptability challenges such as noise onshore, and such as cost, and related technical issues to do with installation and maintenance and climate change offshore. Then we saw some of the challenges facing the wind Power industry with respect to policy instability, and the industry's quite effective response to this.

In the final section we addressed the major choice facing the investment community, and also facing the political decision-making section of the community, regarding the backing of CSG as a bridge to a clean energy future, or the backing of renewables such as wind power and their perfect partner, an integrated, continent wide smart grid, noting that this moment in time is unique and crucial, and the direction taken now will lay the groundwork for the future. In this context, the clearly preferable choice would be the latter option in which the variability of renewable resources is handled by sophisticated regional cooperation and advanced grid technology, with gas playing a relatively minor back-up role as 100% renewable energy progressively becomes the goal, and then the reality.

In this scenario, deep offshore wind farms using floating pontoons would seem to be an ideal mainstay power source using pumped hydro for storage, since the social acceptability issue would be essentially negated deep offshore, and the variability issue would be addressed, and the installation cost issue seems possible to substantially address. Optionality regarding future wind pattern changes due to climate change would be another benefit. Cost effective methods for enabling such systems to be maintained and to survive a factor 5 cyclone will need to be developed however. Other renewable energy forms such as various scales of hydro, Solar PV, solar thermal, wave, geothermal, and biofuels would all find an important role to play, each shining in its own best setting. But wind power has a substantial head start in terms of cost and technical maturity, and will clearly play a substantial role.

For these reasons, the question posed can be answered in the affirmative—modern industrial wind turbines have excellent prospects as a clean energy solution for the future.

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